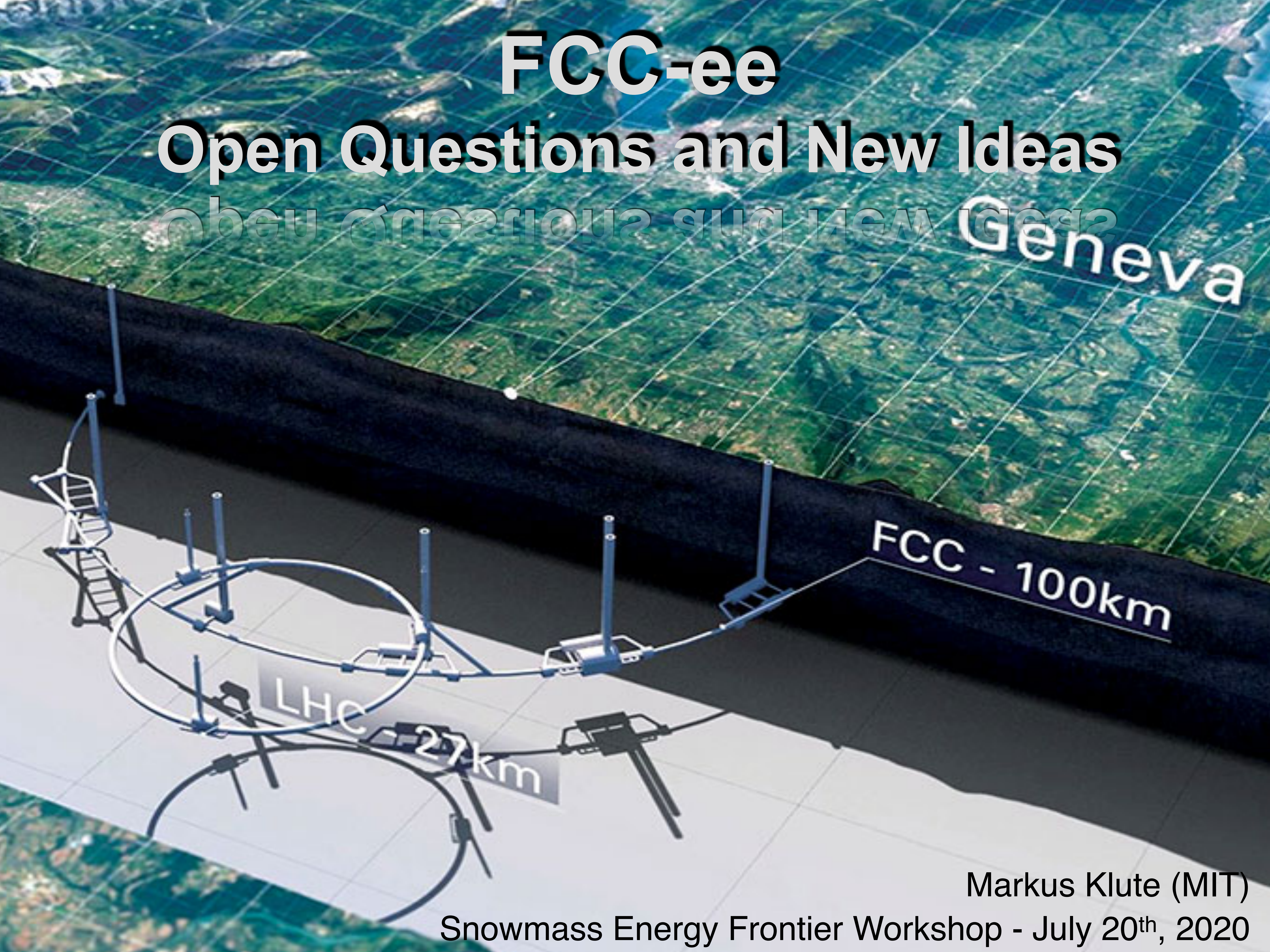
FCC-ee
Open Questions and New Ideas



Markus Klute (MIT)

Snowmass Energy Frontier Workshop - July 20th, 2020

European Strategy

Preamble: The particle physics community is ready to take the next step towards even higher energies and smaller scales. The vision is to prepare a Higgs factory, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated technical and environmental challenges.

High-priority future initiatives

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

the particle physics community should ramp up its R&D effort focused
· on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;

This is work for us in the US!

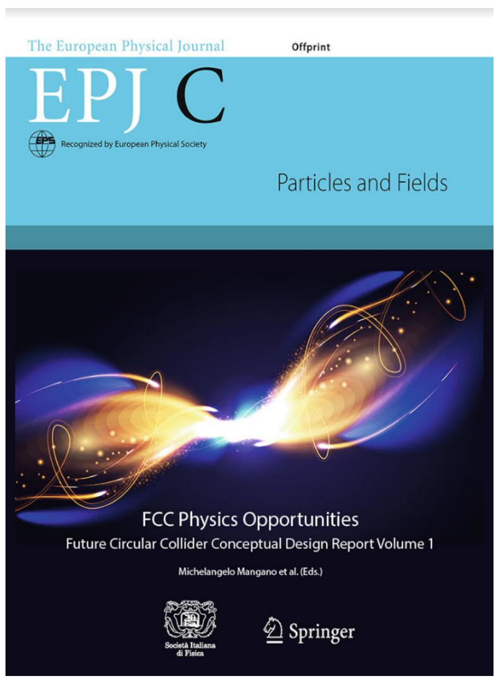
· Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

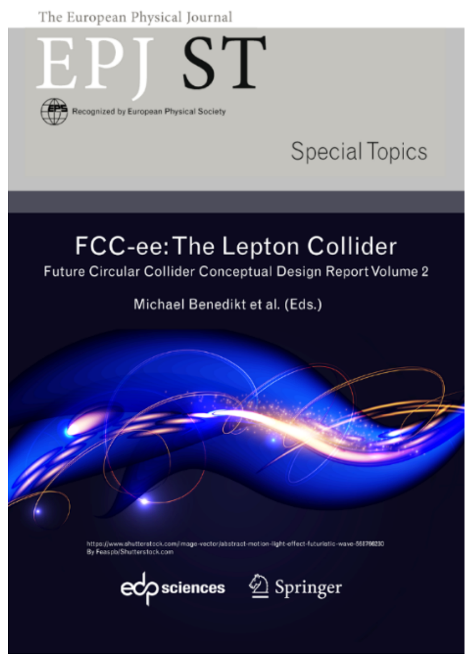
FCC documentation

Outcome of design studies recommended by the 2013 European Strategy

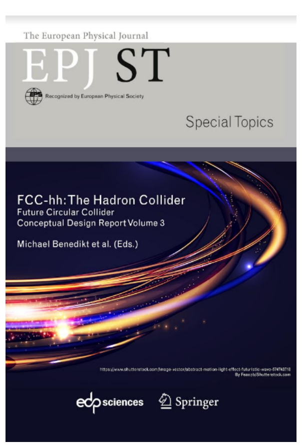
4 CDR volumes published in EPJ



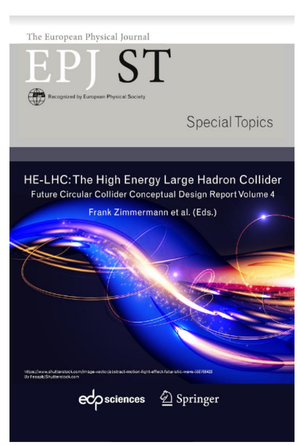
FCC Physics Opportunities



FCC-ee: The Lepton Collider



FCC-hh: The Hadron Collider



HE-LHC: The High Energy Large Hadron Collider

Recent FCC publications

1) Future Circular Collider - European Strategy Update Documents

(FCC-ee), (FCC-hh), (FCC-int)

2) FCC-ee: Your Questions Answered - arXiv:1906.02693

3) Circular and Linear e+e- Colliders: Another Story of Complementarity

arXiv:1912.11871

4) Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders arXiv:1901.02648

5) Polarization and Centre-of-mass Energy Calibration at FCC-ee, arXiv:1909.12245

FCC Main Goals (2020-2026)

Overall goal

- Perform all necessary steps and studies to enable a definitive project decision by 2026, at the anticipated date for the next ESU, and a subsequent start of civil engineering construction by 2029.

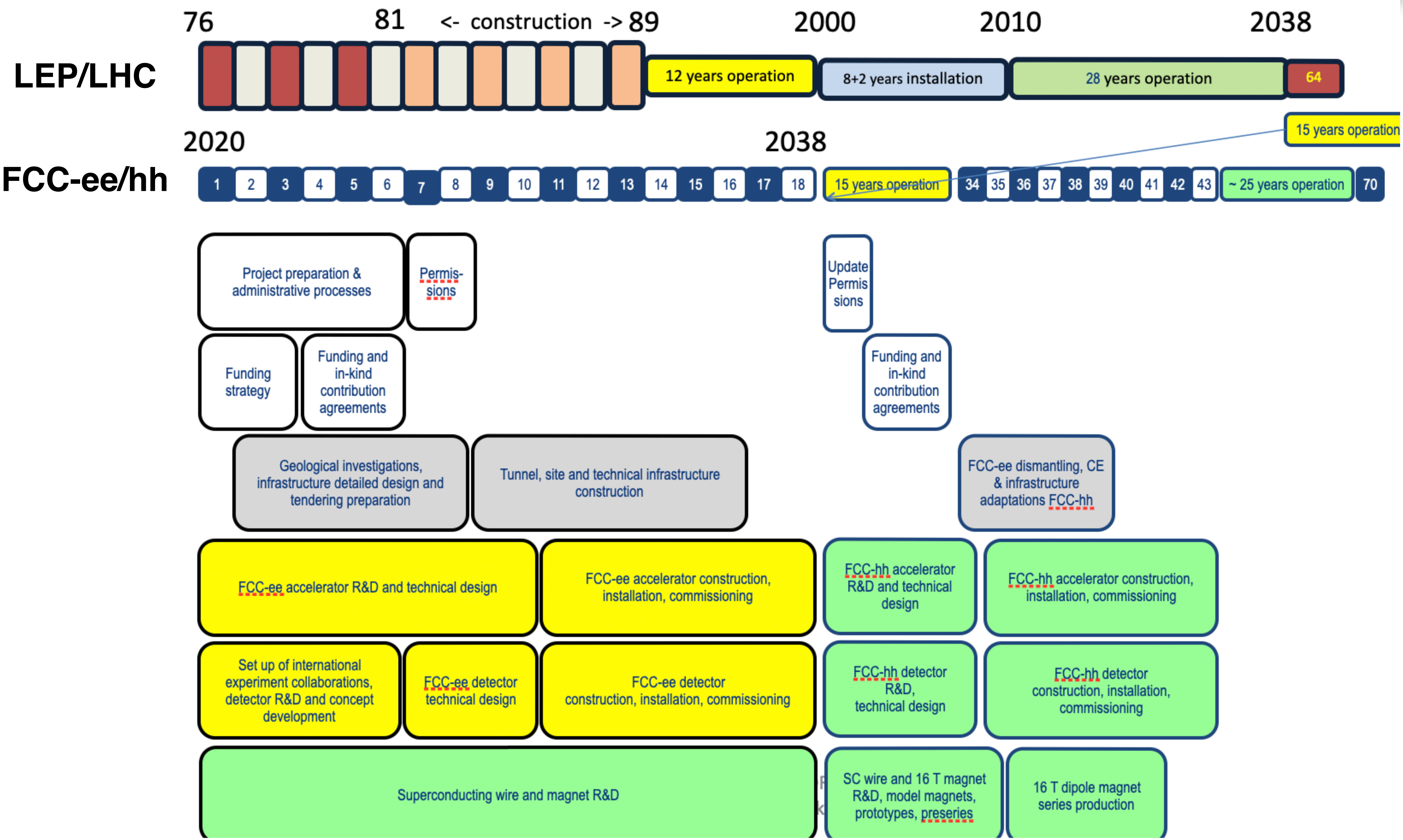
This requires successful completion of the following four main activities

- Develop and establish a governance model for project construction and operation
- Develop and establish a financing strategy
- Prepare and successfully complete all required project preparatory and administrative processes with the host states (debat public, EIA, etc.)
- Perform site investigations to enable CE planning and to prepare CE tendering.

In parallel development preparation of TDRs and physics/ experiment studies

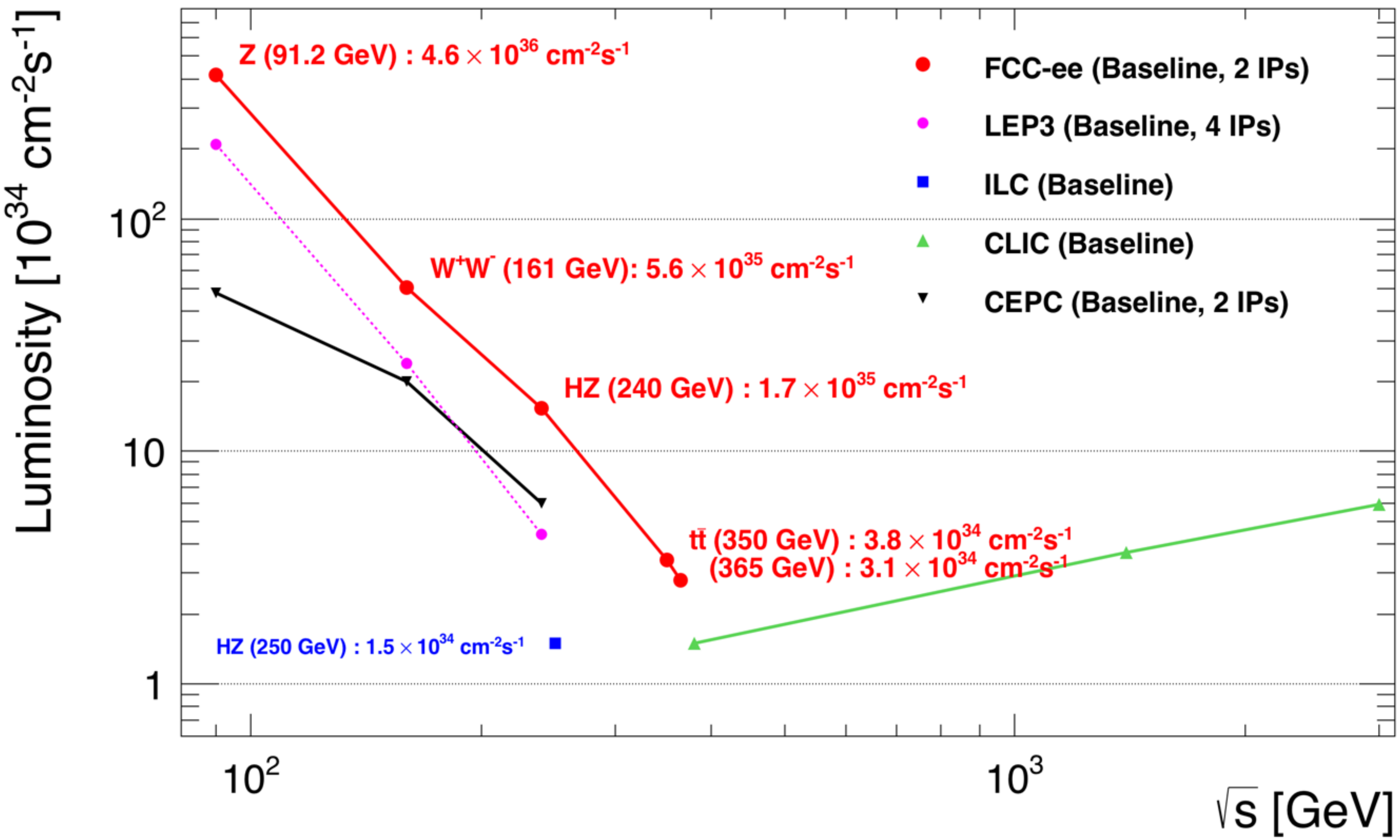
- Machine designs and main technology R&D lines
- Establish user communities, work towards proto-experiment collaborations by 2025.

FCC Technical Schedule



FCC project plan is fully integrated with HL-LHC exploitation and provides seamless continuation of high energy physics at the energy frontier

Physics Results (FCC-ee) Landscape



4 experiments instead of 2
→ x1.7

(4y) Z peak	E_{cm} = 91 GeV	$5\ 10^{12}$	e+e- → Z	LEP x 10^5
(2y) WW threshold	E_{cm} = 161 GeV	10^8	e+e- → WW	LEP x 2.10^3
(3y) ZH threshold	E_{cm} = 240 GeV	10^6	e+e- → ZH	Never done
(4y) $t\bar{t}$ threshold	E_{cm} = 350 GeV	10^6	e+e- → $t\bar{t}$	Never done
(ny) H(optional)	E_{cm} = 125 GeV	10^4	e+e- → $\bar{H}$	Never done
				Never done

E_{CM} errors:

100 keV
300 keV
2 MeV
5MeV
<1 MeV

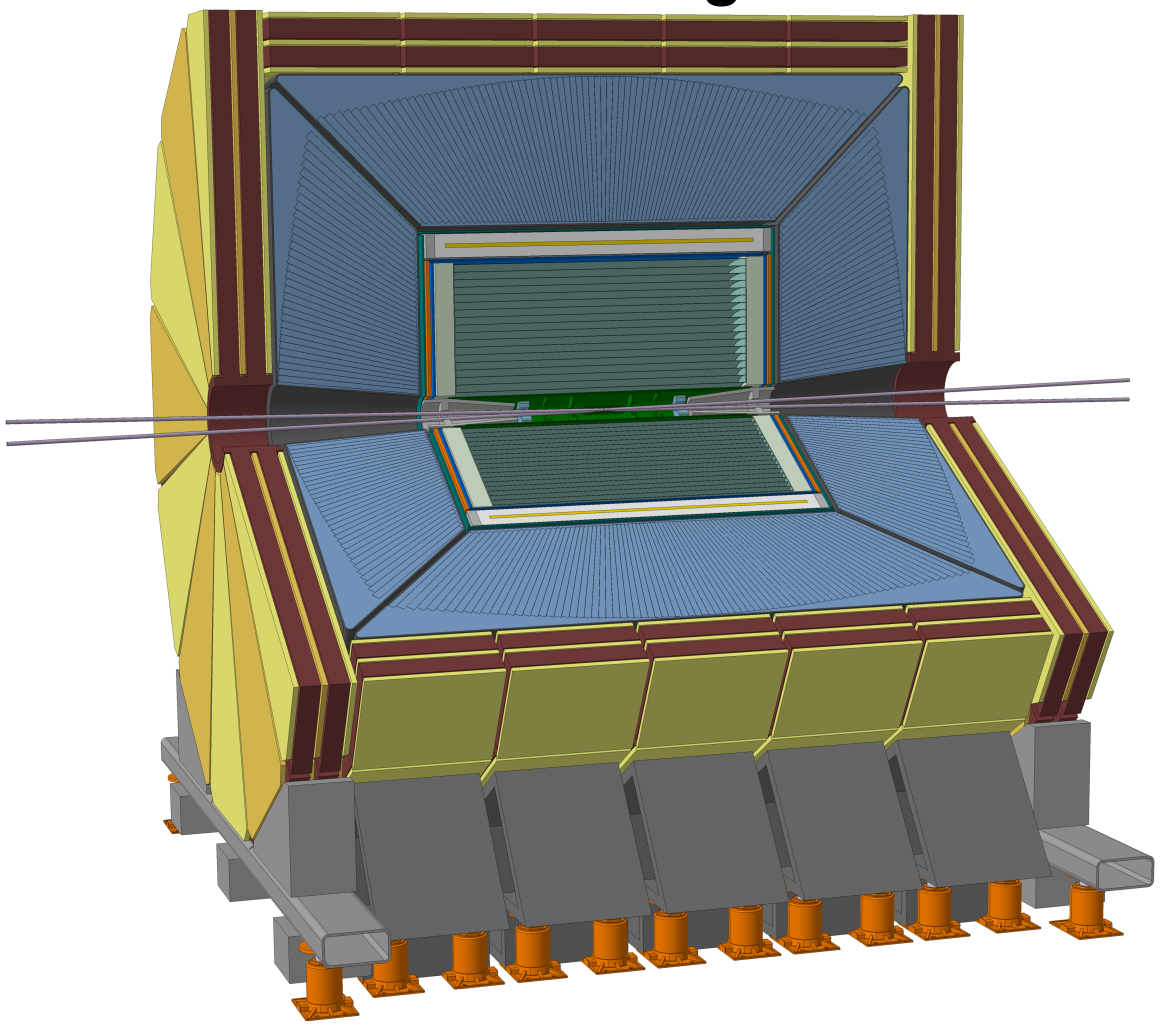
Great energy range for the heavy particles of the Standard Model.
Complementarity with hadron colliders (LHC, FCC-hh) and also with linear colliders

FCC-ee Detectors

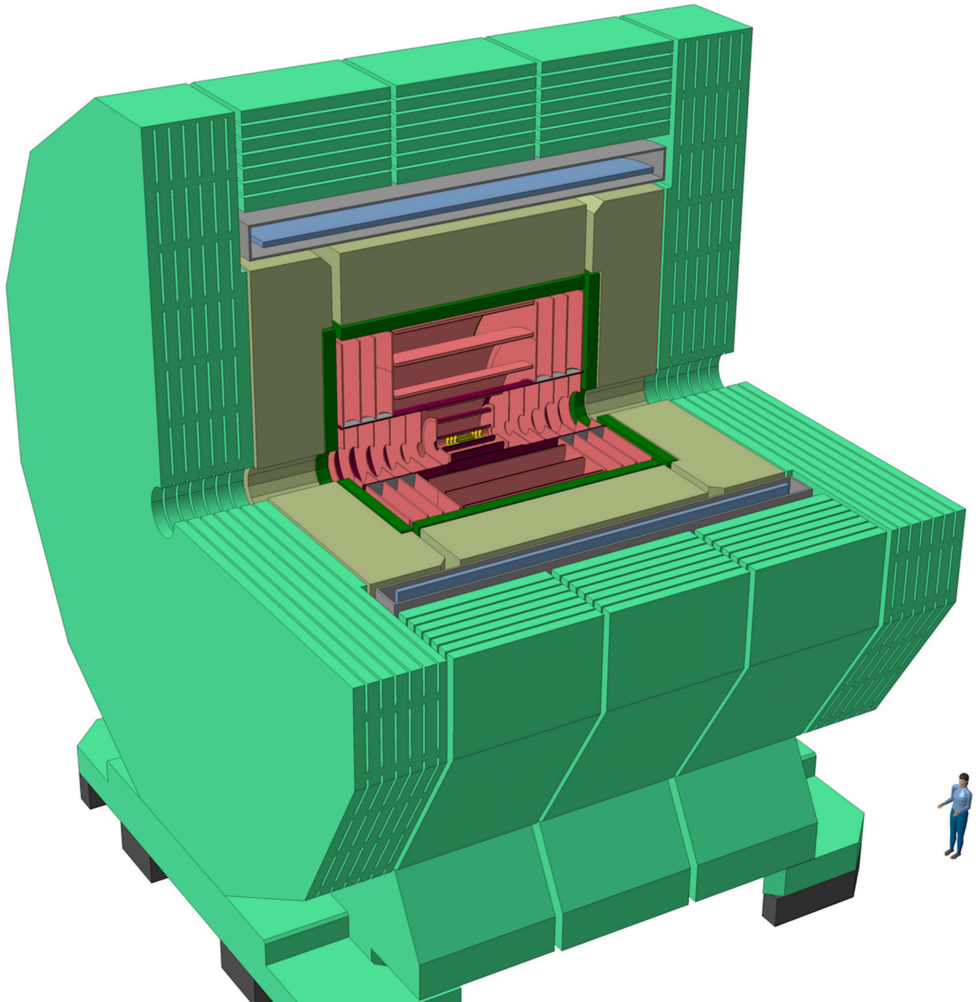
Two detector concepts used for integration, basic performance and cost estimates:

- Linear Collider Detector group at CERN has undertaken the adaption of a detector for FCC-ee
- IDEA, detector specifically designed for FCC-ee (and CEPC)

IDEA design



CERN adapted design



Next step is to design detectors for physics

Opportunity to design multiple collider detector

FCC-ee Higgs Couplings

➡ **Unique measurements at highest precision**

Collider	HL-LHC	ILC_{250}	CLIC_{380}	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+ 1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	8	3	+ 4	–	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.30	0.60	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.3	**0.61**	0.56	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	1.6	**1.01**	0.90	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.4	**0.74**	0.67	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	10.1	**9.0**	3.8	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	4.8	**3.9**	1.3	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	3.1	1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	**< 1.0**	< 1.0	n.a.

Eur. Phys. J. C. (2019) 79:474

➡ **With enough work, uncertainties not limited by experimental or theoretical uncertainties. Statistics sets the floor.**

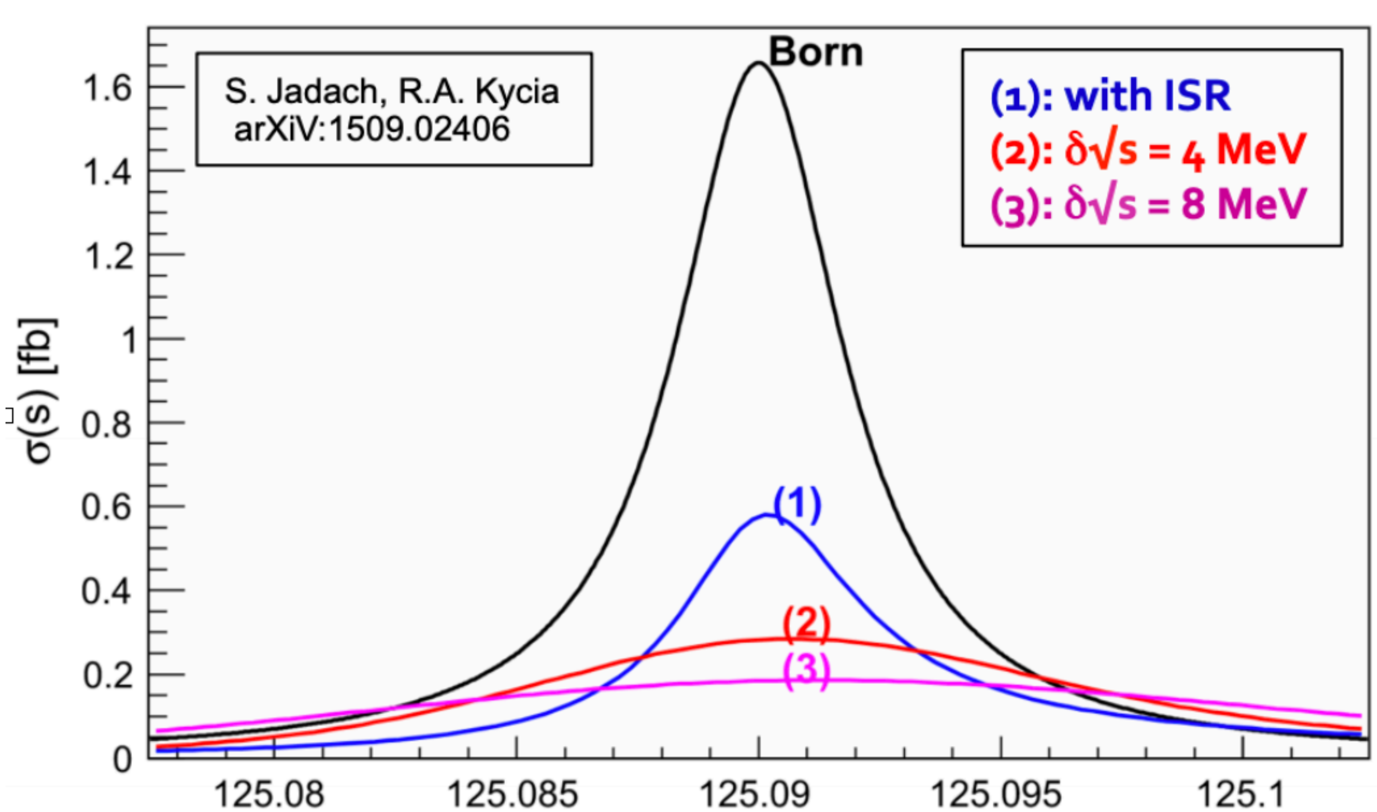
➡ **3-5 standard derivation sensitivity to Higgs self-coupling via ZH cross section dependency**

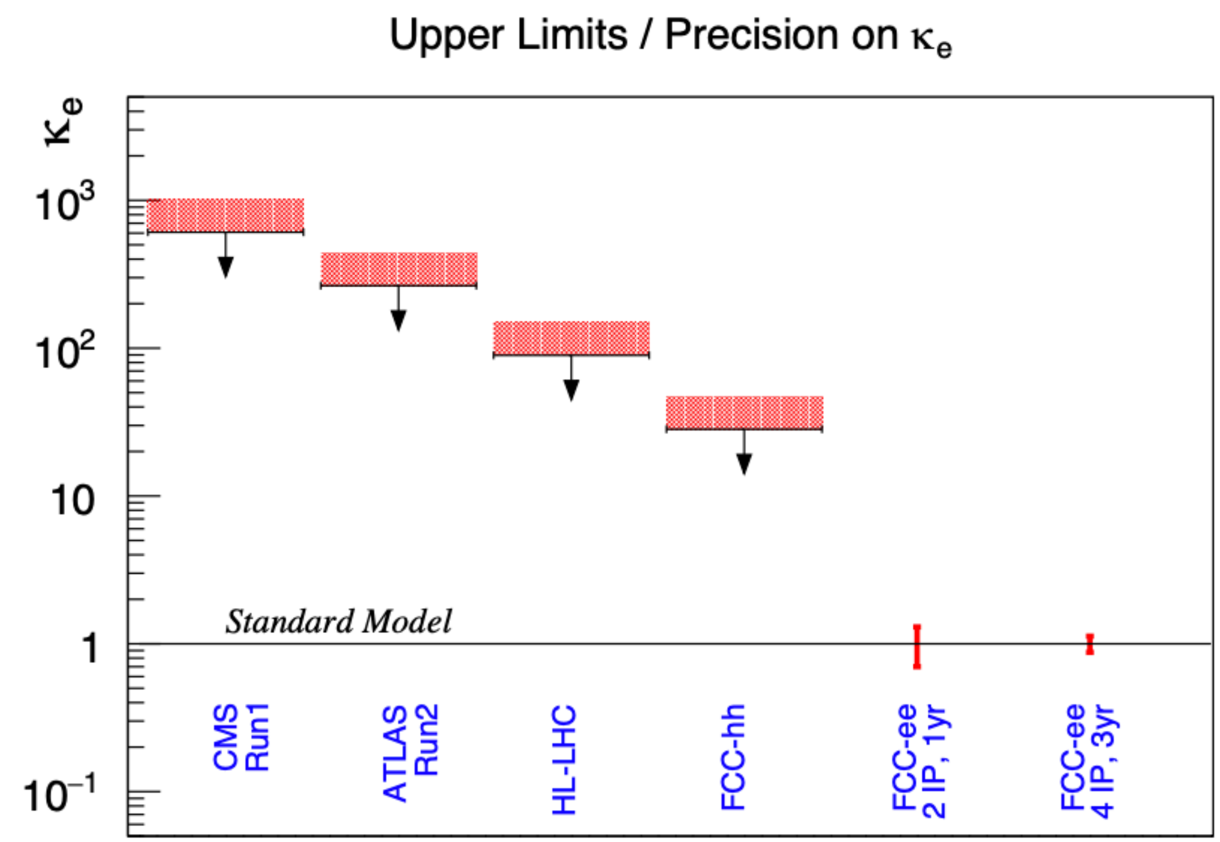
➡ **Complementarity with LHC and FCC-hh program**

Unique measurement at FCC-ee

➡ First generation Higgs couplings

- **Not part of baseline** run plan but a few years at √s = mH with high luminosity and **monochromatization** is an interesting add-on
- **Expected signal significance of 0.7σ / 10ab-1**
  - Set a electron Yukawa coupling upper limit: $k_e < 2.5$ @95% CL
  - Reaches SM sensitivity after 5 years
  - Work ongoing to improve results





FCC-ee EW & Top Physics Program

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ ($\times 10^4$)	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
R_b ($\times 10^6$)	216290 ± 660	**0.3**	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu (\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff} (\times 10^6)$	231480 ± 160	**3**	1	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
$A_{FB}^b, 0$ ($\times 10^4$)	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

First set of main observables - needs to be improved

- **Focus on statistical precision**
- **For Z and W boson mass, center-of-mass energy uncertainty will dominate**
- **For cross-section measurements the luminosity measurement will be limiting**
- **Possible experimental uncertainties are indicative**
- **Tau, b, and c observables to be added**
- **Theory work is critical and has been initiated. A lot of work ahead.**
- **Aim for next study: detector design to match experimental systematic uncertainties to statistical precision**

FCC Memo

MEMORANDUM

From: FCC Physics and Experiments Design Study; M. Benedikt, A. Blondel, P. Janot, M. Mangano
To: Snowmass conveners
Object: Participation to the 2020-2021 Snowmass Study

Introduction

The Future Circular Collider (FCC) physics, experiment and detector study groups are happy to get involved with the 2020-2021 Snowmass Study and welcome contributions from its participants. The FCC project is presented in the FCC CDRs [1][2][3][4], and in the contributions to the European Strategy [5][6][7][8][9][10] and in the recent physics workshop [11]. Further official FCC results, expected to be produced as time develops, will be summarized in one or several Snowmass contributions in 2021.

A general introduction to the FCC is given in a recent *Nature* article [12]. The FCC project comprises a first step consisting of a high-luminosity e^+e^- collider with centre-of-mass energy varying from 90 to 365 GeV, starting at the end of HL-LHC, to be followed in the 2060's by a 100 TeV pp collider including a program of ion-ion collisions and an e-p collider option. The FCC, making use of the complementarities and synergies of the lepton and hadron colliders, is an exceptionally powerful facility for Higgs studies. The FCC offers unmatched opportunities for direct production of new particles, both at feeble couplings and at high masses, with the lepton collider Z factory on the one hand, and the 100 TeV hadron collider on the other. It is also unique for electroweak physics both in neutral and charged currents, for QCD precision studies, and for the detailed exploration of heavy quark and lepton flavour properties. The unique features of the circular e^+e^- Higgs, Electroweak and Flavour factory are compared with those of the linear colliders in Ref. [10].

The FCC has recently received a 4-years grant from the European Union in support for a Design Study (FCC-IS) of the preparation of implementation of the infrastructure and lepton collider as first step of the FCC project. The task of the FCC physics, experiments and detector studies in the next 5 years is to deepen the studies, identify the detector requirements to match the much reduced experimental statistical uncertainties, promote the suitable detector R&D, and work towards establishing global experimental FCC-ee proto-collaborations by 2026/27.

Contact persons

The contact persons from the FCC physics and experiments studies to the Snowmass study frontiers are as follows:

- Overall contact: Markus Klute, plus Alain Blondel, Patrick Janot and Michelangelo Mangano
- Energy Frontier: Patrizia Azzi and Gregorio Bernardi (FCC-ee), Michele Selvaggi (FCC-hh), Christophe Grojean (Phenomenology)
- Frontiers in Rare Processes and Precision Measurements: Stéphane Monteil (b and c physics) and Mogens Dam (τ physics)
- Theory Frontier: Matthew McCullough
- Instrumentation Frontier: Mogens Dam and Franco Bedeschi
- Computational Frontier: Luc Poggioli

Software support can be obtained from the FCC software group (see C. Helsens and G. Ganis in [14]) who will be happy to integrate software contributions.

New results and challenges

Although a considerable amount of information is already included in the documents cited above and in the Physics Briefing Book [13] prepared by the European Strategy Preparatory Group, we would like to bring the following to your attention.

The FCC-ee accelerator design and luminosity figures are considered solid for the baseline configuration with two interaction points (2IP). The operation of detectors on the FCC-ee was shown to be feasible. A 4IP configuration is being studied, with the aim of delivering a total luminosity of a factor 1.7 higher for the same collider power consumption as that of the 2IP baseline. A "mono-chromatization" scheme is under study to make it possible to achieve the detection of $e^+e^- \rightarrow H$ production in the s channel.

The exceptionally large event samples expected at the FCC colliders constitute a challenge for detector design and construction quality, and also for computing. The FCC design study is relatively new in these respects. Considerable improvement and optimization of the detectors and of the running mode can be expected, thus offering numerous opportunities for ingenuity and creativity, to which we are happy to invite the Snowmass participants.

We can give two recent notable examples here.

1) Improved investigations [9] of the centre-of-mass energy calibration for the Z resonance scan lead to uncertainty estimates reduced to $\pm$ 25 keV on the Z width, $\pm$ 3.1 x 10^{-6} on $\sin^2\theta^{eff}_{lept}$, and a direct measurement of $\alpha_{QED}(m_Z)$ with a $\pm$ 3 x 10^{-5} relative precision. Improved analysis, instrumentation and monitoring might reduce these experimental errors even more.
2) Further investigation of the double Higgs production at FCC-hh [15] has led to an improved expected statistical precision of O($\pm$2%) with the full exposure, implying that the 10% precision mark should be reached very early (2-5 years) in the life of FCC-hh.

A set of "case studies" is being compiled in view of establishing a list of benchmarks and detector requirements, and will be contributed as one or several LOIs in the near future. Many other opportunities exist, to be identified and studied by the Snowmass participants.

Theoretical Challenges

All future lepton colliders proposed for the High Energy and Precision Frontier set stringent demands on theory to match the experimental precisions [16]. The most ambitious, broad-reaching and demanding of them is FCC-ee. This tremendous challenge is also an opportunity for the theory community to play an essential role in a combined precision calculation and measurement campaign, which could eventually lead to far-reaching constraints or discovery. It was concluded in Ref. [17] that the challenge can be tackled by a distributed collaborative effort in academic institutions around the world, provided sufficient support is available. We certainly encourage the Snowmass study to consider this essential endeavour in its future planning.

With our best wishes for a successful SNOWMASS 21!

References

Physics Performance Group coordinated by
Patrizia Azzi (INFN Padova) and Emmanuel Perez (CERN)

Case Studies

A selection of benchmark studies at FCC-ee

Contribution to Snowmass 2021

Abstract

The FCC-ee is a frontier Higgs, Electroweak, and Flavour factory, to be operated in a 100 km circular tunnel built in the CERN area. In addition to offering an outstanding and largely unique physics program, it serves as the first step of the FCC integrated programme towards 100 TeV proton-proton collisions in the same infrastructure. A selection of significant benchmark studies is proposed. The focus is on measurements that are either unique, or for which the high statistics of FCC-ee lead to the most demanding requirements on detector design or on theoretical calculations. The ultimate goal is that experimental or theory systematic errors match the statistical limit. The list presented in this document is not exhaustive, and will evolve in time.

Submitted as LOI.
Individual contributions to follow.

A non-exhaustive list of studies is presented below. A more extensive document with short descriptions of each of them is available at https://www.overleaf.com/read/dyjpdszrqxhz; it will be regularly updated with more case studies and contacts. Meanwhile, Alain Blondel, Patrick Janot, and Markus Klute are the main entry points to these case studies.

Preparing a FCC software tutorial
August 25-27

A first list of benchmark studies

1. Towards an ultimate measurement of $R_\ell = \frac{\sigma(\mathrm{Z}\to\mathrm{hadrons})}{\sigma(\mathrm{Z}\to\mathrm{leptons})}$
2. Towards an ultimate measurement of the Z total width Γ_Z
3. Towards an ultimate measurement of the Z peak cross section
4. Direct determination of $\sin^2\theta^\ell_\mathrm{eff}$ and of $\alpha_\mathrm{QED}(m^2_\mathrm{Z})$ from muon pair asymmetries
5. Determination of the QCD coupling constant $\alpha_\mathrm{S}(m^2_\mathrm{Z})$
6. Tau Physics, Lepton Universality, and Lepton Flavour Violation
7. Tau exclusive branching ratios and polarization observables
8. Z-pole Electroweak observables with heavy quarks
9. Long lived particle searches
10. Measurement of the W mass
11. Measurement of the Higgs boson coupling to the c quark
12. Measurement of the ZH production cross section
13. Measurement of the Higgs boson mass - Part I
14. Measurement of the Higgs boson mass - Part II
15. Inferring the total Higgs boson decay width - Part I
16. Inferring the total Higgs boson decay width - Part II
17. Determination of the HZγ effective coupling
18. Electron Yukawa via s-channel $\mathrm{e^+e^-} \to \mathrm{H}$ production at the Higgs pole
19. Measurement of top properties at threshold and above
20. Search for FCNC in the top sector
21. Theory Needs for FCC-ee
22. Beyond MFV: constraints on RH charged currents and on dipole operators
23. Construction of CP-odd observables to probe CP-violating Higgs couplings
24. Combined fit of Higgs and top data

Case Studies

11 Measurement of the Higgs boson coupling to the c quark

The SM Higgs boson is expected to decay to $c\bar{c}$ with a branching ratio of about 3%. This decay will be extremely difficult to isolate and measure at LHC, but is directly accessible at FCC-ee if an efficient c-tagging algorithm, able to disentangle $c\bar{c}$ decays from other copious hadronic Higgs boson decays ($b\bar{b}$ and gg, and to a lesser extent, ZZ* and WW*) with high purity, can be designed. An ideal (100% efficient and 100% pure) tagging algorithm would yield a measurement of $\sigma_{ZH} \times \mathrm{BR}(\mathrm{H} \to c\bar{c})$ with a precision better than 1%.

Starting from the related experience developed at LHC and other e^+e^- collider projects, and with the help of the latest machine-learning technologies, such an algorithm will be developed, first with fast simulation, and then in the full context of the constraints from the interaction region and detector layout. The impact of the interaction-region and detector design (beam pipe radius, vertexing, vertex mass determination, tracker material, ...) on the precision $\sigma_{ZH} \times \mathrm{BR}(\mathrm{H} \to c\bar{c})$ measurement will be studied. As a by-product, similar studies for the $\mathrm{H} \to b\bar{b}$ and $\mathrm{H} \to gg$ decays will be conducted as well. The need for calibration data at the Z pole will be estimated (frequency, number of events).

- ➡ Measurement of charm quark Yukawa coupling (b and gluon)
- ➡ Starting from LHC and lepton collider experience and using DNN
- ➡ First studies with fastSim (Delphes) and later with fullSim taking constraints of interaction region and detector layout into account as well as available calibration data
- ➡ Goal: understand/optimize performance with modern detector, 1cm radius beam pipe and very clean experimental environment. Find best compromise between granularity and low mass detector, use of PID. Add analysis at Z (10^{12} bb events!) to understand self –calibration and systematics.

Case Studies

6 Tau Physics, Lepton Universality, and Lepton Flavour Violation

The 10^{11} τ pairs produced at FCC-ee offer a number of measurements that are sensitive to the existence of heavy physics and should be included in global fits, such as those involving right-handed neutrinos. The statistical uncertainties will be more than two orders of magnitude smaller than present values. The studies will aim at matching the detector systematics with the statistics available and derive the key detector requirements, which are expected to be some of the most demanding ones. The measurements involved (and corresponding assumed leading detector requirements) are, in particular, as follows:

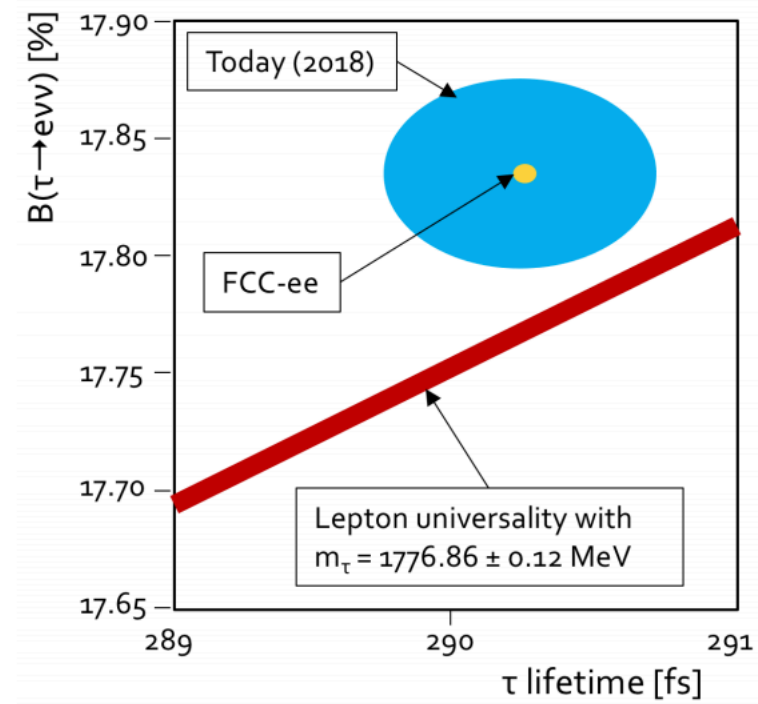
i) the tau lepton lifetime (and the vertex detector radial alignment);

ii) the tau lepton mass (and the tracker momentum scale);

iii) the tau leptonic branching ratios (and lepton efficiency and identification);

iv) the tau flavour violating decays $\tau \to \mu/e\ \gamma$, etc. (and the lepton momentum resolution).

A first review with many references was made by M. Dam [12].



Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

arXiv:1811.09408

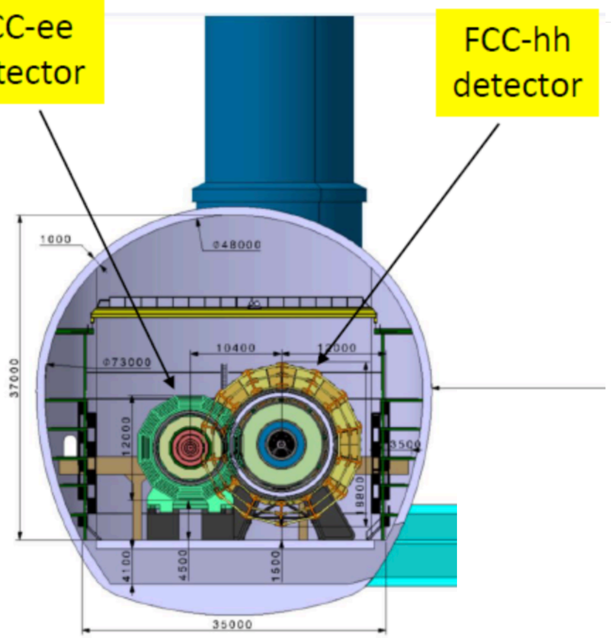
- ➡ Utilizing enormous number of Z decays to taus to improve statistical uncertainties by two orders of magnitude
- ➡ Goal: study detector systematics and derive key detector requirements. Can systematic uncertainties meet statistical precision?

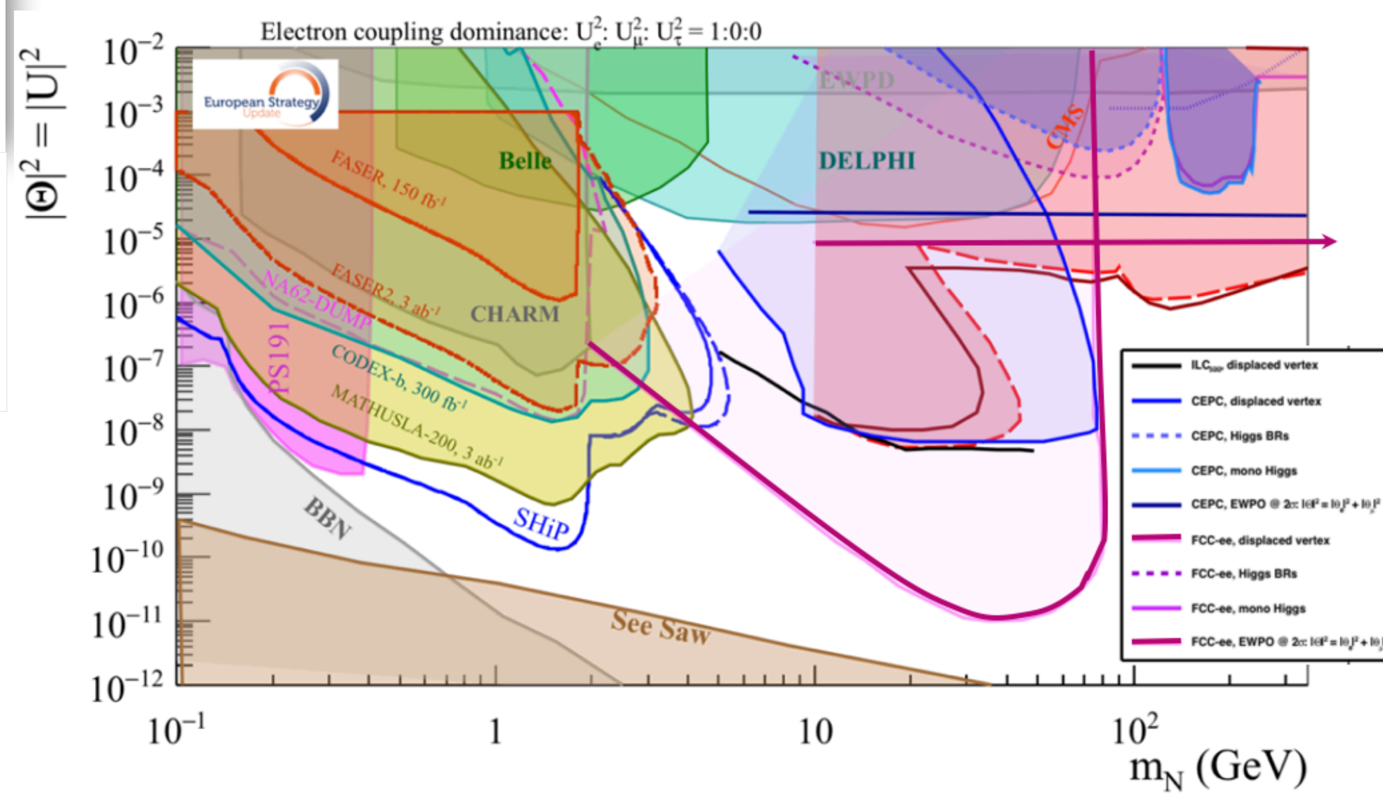
Quantity			LEP	FCC-ee
Impact parameter resolution	$\sigma_d = a \oplus \frac{b \cdot \mathrm{GeV}}{p_\mathrm{T} \sin^{2/3}\theta}$	a	20 μm	3 μm
		b	65 μm	15 μm
Momentum resolution	$\frac{\sigma(p_\mathrm{T})}{p_\mathrm{T}} = \frac{a \cdot p_\mathrm{T}}{\mathrm{GeV}} \oplus b$	a	6×10^{-4}	2×10^{-5}
		b	5×10^{-3}	1×10^{-3}
ECAL energy resolution	$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E/\mathrm{GeV}}} \oplus b$	a	0.2	0.15
		b	0.01	0.01
ECAL transverse granularity			15×15 mrad^2	3×3 mrad^2

Case Studies

9 Long lived particle searches

The Tera-Z run will allow for the direct search of new feebly interacting particles that could be good Dark Matter candidates (ALPS, Dark Photon, HNL Sterile Neutrinos). In some cases, the relationship in the model parameters is such that the final state would include a particle with a very long lifetime and detached vertex, for instance as in the case of a heavy sterile neutrino. A sensitivity down to a heavy-light mixing of 10^{-12} was obtained, covering a large phase-space for heavy neutrino masses between 5 and 80 GeV [15]. The signal events would be characterised by the Z decaying $Z \to \nu N$ followed by $N \to W^{*}\ell$ or $Z\nu$. For low values of the mixing angle the decay length of the HNL can be significant, and correspond to a decay vertex at the edge of the tracking volume or beyond. In order to achieve the ultimate sensitivity for these type of events it is necessary to develop, among other things, new tracking and vertex reconstruction algorithms. These algorithms would have to be re-optimised for the different detector concepts (silicon tracker, drift chamber, etc). In turn, these studies could bring in ideas for innovative solutions for new, possibly very large (the caverns being designed already for the FCC-hh detectors), tracking detectors or co-processors that would be optimal for these type of searches in unusual final states





➡ Long lived particle search like heavy sterile neutrinos

➡ Goal: find additional detector requirements (opportunities) or concepts to increase sensitivity to exotic particles

➡ **Looking for innovative solutions**

21 Theory Needs for FCC-ee

The FCC-ee is at the High Energy and Precision Frontier and will provide a set of ground-breaking measurements of a large number of new-physics sensitive observables, with improvement by one to two orders of magnitude in experimental precision. The full exploitation of the significantly increased experimental precision in Z-pole observables, W boson and top quark masses, and a broad array of Higgs observables, necessitates SM predictions accurate at a level commensurate with this precision. In this submission we outline the numerous opportunities for significant theoretical and experimental impact through the furtherance of EWPO calculations in the SM, both for electroweak and QCD sectors, and highlight the need for the development of new methods and tools for higher order perturbative calculations. The FCC-ee is a multi-decade project offering theoretical challenges on a comparable timescale.

Conclusion

- **FCC-ee offers a huge physics program** with
  - ➡ Higgs and top measurements with > 10^6 events each in short (3-5y) runs
  - ➡ Unique possibilities
    - Electron Yukawa coupling
    - TeraZ + beam energy calibration
    - keV and ppm precision on EWPOs at Z resonance and WW threshold
    - $\alpha_{QED}(m_Z)$, $\alpha_S(m_Z)$, $\sin^2\theta_W^{eff}$ and $G\tau$
    - Searches for LLPs and rare phenomena (LFV, LNF, light scalars, ...)
    - Flavor physics program with 10^{12} Bs and 10^{11} τ's
    - Offering sensitivity to new physics at scales of 10 to 70 TeV
- Ambitious program aiming for significant progress in understanding of nature
- Main challenge is to imagine/optimize detector to match statistical power and to sharpen the theory calculations
- Last but not least: an essential springboard towards 100 TeV pp collisions